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Science Requirements Document

For

**Growth and Extinction Limit of solid fuels
(GEL)**

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Executive Summary

Flammability of solid materials is of interest to NASA as a first line of defense in spacecraft fire safety efforts. In micro- or partial-gravity, the reduced buoyant flows, coupled with low-speed air circulation currents, create an environment quite different than that in normal Earth gravity. In addition, there are several oxidizer atmospheres under consideration for crew vehicles and habitats, which expand the scope of the problem. A fundamental understanding of solid flammability as a function of gravity, flow velocity, oxygen percentage, pressure, and sample configuration can be an important contribution both to combustion science and to the NASA space exploration initiatives.

This proposed experiment will concentrate on the flame growth, decay and extinction over the surface of a non-flat thick solid in microgravity. In particular, a solid sphere of substantial size (i.e. 4 to 5 cm diameter) is chosen as a representative of non-flat samples. In addition to the parameters influencing the flammability in thin solids, the degree of interior heat-up is an important parameter on the solid burning characteristics of thick specimen. In spherical samples, the degree of interior heating is always changing. The problem is therefore unsteady in nature. In addition, flow around a sphere is different from that around a flat surface. The existence of a forward stagnation point, shoulder and wake regions result in different local flow pattern, hence a different flame-solid interaction. These can affect the burning and extinction characteristics.

In the proposed experiment, cast Polymethylmethacrylate (PMMA) spheres will be instrumented with several imbedded thermocouples to record the interior temperatures during the preheating and the combustion processes. The project objectives are (1) Experimentally determine the flame growth characteristics (growth rate, flame shape and dimensions) over thick

solid fuel as a function of flow velocity, oxygen percentage, pressure and the degree of internal heating, (2) Experimentally determine the flame extinction characteristics (quenching and blowoff limits) over thick solid fuel as a function of flow velocity, oxygen percentage, pressure and the degree of internal heating and (3) Establish a high-fidelity numerical model that can be compared with the microgravity results and to serve as a tool connecting normal gravity and microgravity performance.

The proposed experiment is to be conducted in the International Space Station (ISS) because ground-based microgravity facilities cannot provide the test time duration needed for thick samples. Both the Combustion Integrated Rig (CIR) and the Microgravity Glove Box (MGB) can accommodate this experiment. CIR is preferred since it has the additional capability to vary pressure as a parameter.

1 Introduction and background

The main purpose of studying flame spread over solid fuels in microgravity environment is to remove the buoyancy induced flow that always exist in normal gravity. As one type of non-premixed (diffusion) flames, solid combustion can be profoundly affected by the flow (convective) velocity of the oxygen near the sample. Flow velocity can affect the burning intensity, extinction and ignition limits and flame spread rate. In buoyant environment, the induced velocities also vary with distance that further complicates the description. For extinction, a simple flammability map has been used in the past to highlight the effect of velocity especially in the low-velocity regime. A generalized map is shown in Fig. 1. The flammability boundary is U-shaped with a blowoff branch on the right hand side and a quenching branch on the left hand side. Blowoff represents a high intensity and strong flame that is not able to stabilize due to too short a gas residence time (Damkohler number too small). Quenching represents a low-intensity and weak flame with low flame temperature due to excessive heat loss (radiation and conduction). The U-shaped boundaries shown appear quite generic. For example, depending on the problems, the abscissa in Fig. 1 can be the flame stretch rate (or the flow strain rate), the flow velocity, the gravity level, a rotating rate (for a spinning sample), the inverse of droplet or particle diameter. The ordinate can be the ambient oxygen percentage or the ambient pressure. In general, reaching quenching branch requires the elimination (or a great reduction) of gravity. Flame behavior of low-intensity flames and the determination of quenching extinction limits have been a major part of microgravity combustion research in the recent past [1] and in the present time.

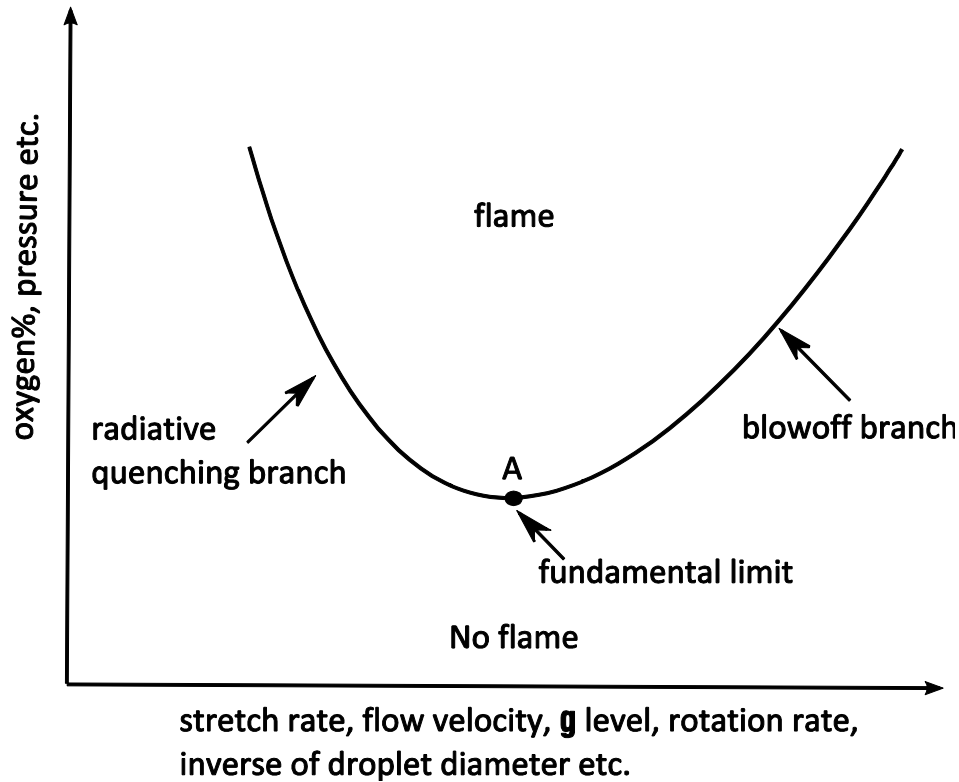


Fig.1 A generalized flammability limit map to qualitatively demonstrate the existence of a flame blowoff branch and a quench branch[2].

When describing the flammability of thick (or more precisely “thermally-thick”) solid fuels, additional complication arises beyond those displayed in Fig.1. This has to do with the description of the percentage of gas-phase heat transfer going into the solid interior from the flame. For example, in the burning of solid sample in a stagnation flame, the first work demonstrated the U-shaped flammability boundary[3], the thick solid sample is assumed to reach a steady interior temperature field. This steady distribution is the balance between the rate of conduction into the solid and the solid surface regression rate. In other word, it is a convection-diffusion balance in a coordinate system attached to the solid surface. For typically solid burning, the time to reach the steady temperature distribution can be quite large. Take PMMA in air for example, we estimated the time scale is between 1 to 5 minutes depending on the flows. Before

reaching steady burning, the percentage of gas phase heat feedback going into the solid interior is greater. In such situations, the gas flame is less flammable.

To illustrate the effect of flame heat loss to the solid, a simplified burning model of PMMA cylinder has been solved in a cross flow[4]. The model is two-dimensional. The cylinder is placed in a channel with height four times of the cylinder diameter. The wall is assumed to have slip boundary condition (alternatively this problem can be viewed as an infinite row of cylinders). The problem is solved assuming a succession of quasi-steady states. Each case a fixed percentage of gas-phase heat feedback to the solid going into the solid interior is assumed. Same percentage is also assumed to be at every part of the cylinder surface. The model has complete Navier-Stokes equations with one step finite rate kinetics and surface radiation loss. The computed flammability boundary in air (21% oxygen) is shown in Fig. 2 with the percentage of heat flux into the solid ϕ and the free stream velocity U_∞ as coordinates. The envelop flame boundary has a \cap shape. At low velocity, the flame goes out as a shrinking short flame near the forward stagnation point due to heat loss (quenching branch). At higher velocity, the envelope flame first retreats from the forward stagnation point to form a wake flame before a complete blow-off at even higher velocity. The high velocity blow-offs at both the forward stagnation region and the wake are due to short residence times (small Damkohler numbers), similar to that shown in Fig.1. However, instead of ambient oxygen % or pressure, the ordinate in Fig. 2 is the percentage of heat flux going into the solid interior ϕ . The widest flammable velocity range occurs when there is no heat feedback going into the solid interior $\phi=0$, i.e. when the solid is uniformly at the pyrolysis temperature. With more heat losses into the solid interior, the flammable range of flow velocity shrinks. Above a critical ϕ (≈ 0.56 in Fig.2), the solid is not flammable at any flow velocity.

Fig. 3 shows the flame shapes as a function of flow velocity. At low velocity, the flame wraps around the front part of the cylinder. Further decreasing the flow velocity increases the flame standoff distances from the solid surface and shortens the flame length. Quenching extinction occurs when the flame becomes too small at the forward stagnation point. Increasing velocity elongated the flame. At a critical flow velocity, the flame at the forward stagnation point is blown off. This local blow-off yields a wake flame as shown in the bottom two plots in Fig. 3. The blowoff of the wake flame (total blow-off) occurs at even larger flow velocity.

Despite some of the simplified approximations (e.g. a uniform ϕ along the cylinder surface), the model does reveal an important physics aspect, i.e., the larger the gas phase feedback going into the solid interior, the less is the flammable range of solid sample. The burning of a thick solid normally starts with an ignition and the heat-up of a shallow layer next to the surface. This is the condition of large loss to the solid interior (large ϕ in Fig. 2), so it is a weaker flame. As burning goes on, the thermal wave penetrates more deeply into the solid, ϕ decreases and the solid becomes more flammable with a more rigorous burning process. This is consistent with our experience with the burning of thick solid such as wood blocks, for example. It is also observed in the on-going space experiment BASS (to be discussed later).

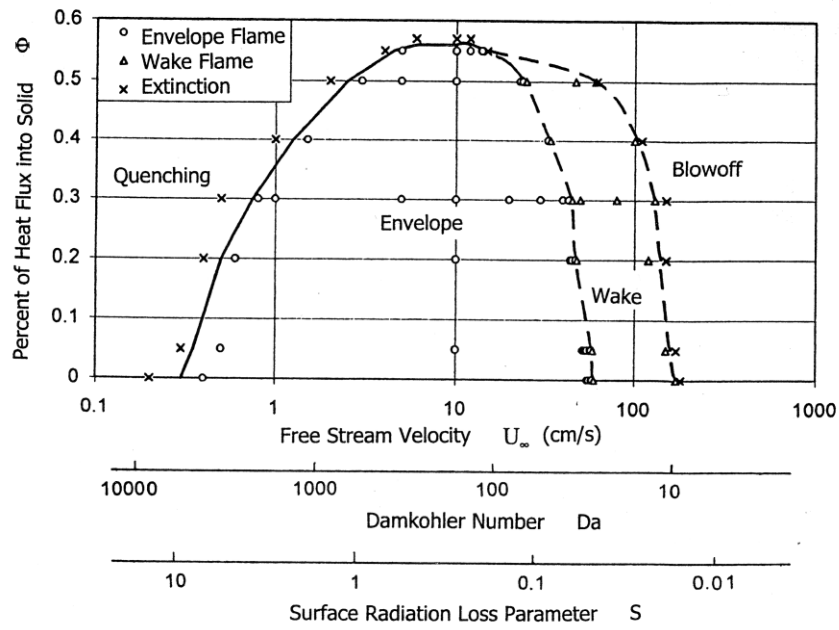


Fig. 2 Flammability boundary of a solid cylinder in cross flow in air (21% O_2) at 1.0 atm[4]

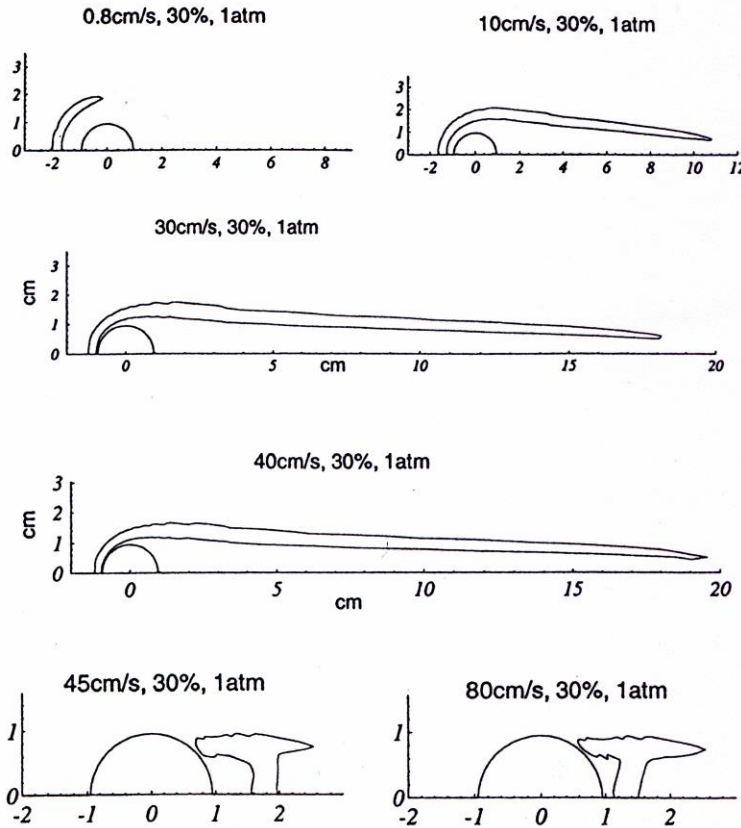


Fig.3 Modeled flame shapes as a function of upstream velocity in 21% O_2 , 1 atm. pressure and $\phi = 0.3$. Flame quenches at $U_\infty = 0.5$ cm/s and total blowoff at 150 cm/s [4]

What the model computation in [4] reveals is that (1) the flame appearance near extinction over a blunt solid is more complicated than that for a flat fuel and (2) the extinction limits of a thick solid cannot be defined precisely without knowing the internal temperatures of the solid sample. In this proposed project on solid flammability, a non-flat fuel (i.e. initial a sphere) will be employed and one of the emphases is to obtain more information on solid in-depth temperature. It will be achieved by a using imbedded thermocouples combined with computed theoretical results.

A remark on the existing material screening process for spacecrafts (NASA-STD-6001 Test1)

NASA-STD-6001 test1[5] is a material screening test that is currently used for space exploration. In this test, material sample 30 cm by 6.5 cm (with 5 cm width exposed) is held vertically and ignited from the bottom. For a material to pass this test, it must not burn more than 15 cm and must not propagate a flame by the transfer of burning debris. The materials that passed this test will be ranked according to the burning process (i.e. burn length).

The validity of this test has been questioned by many researchers in the past most on the influence of flows (i.e. buoyant vs. forced [6]). It is known that some materials have the tendency to be more flammable in micro gravity than normal gravity [Olson et al??]. From the point of thick solids, the test results may depend on the strength of the ignition source which provides the initial heating. For a material that fails the test, it is known that we may be able to pass the test simply by increasing its thickness. This further demonstrates the importance of the degree of internal heat-up on flammability. The NASA 6001 test can be viewed a go/no-go flammability test for some (especially thinner sample) but an ignition test for the others (e.g. thicker sample). In both cases, gravity plays an important role.

2. Review of previous investigations of thick solids in microgravity

Before reviewing the work in microgravity, we like to say a few words on the normal gravity investigations. There is an abundance of research on flame spread over thick solids in normal gravity. As a matter of fact, thick solids are the most common ones investigated because they are the ones in most practical applications. In concurrent flow,

tests are typically upward spread over flat samples. With a few exceptions, most are transient flame growth experiments since the length of upward flame are typically long compared to the sample length [refs???]. There were reports of accelerated flame growth due to increased radiation feedback from soot in large flames of PMMA samples [7, 8]. On the other hand, there was also report on flame reaching of a limiting length in the upward burning of large samples of wood [9]. For thin solids and narrow samples, steady spread with a constant flame length has been routinely achieved in normal gravity[10, 11] and in partial gravity [12]. The mechanisms of reaching a steady limiting length can be either due to cooling by lateral air entrainment (in the case of narrow samples) and/or due to surface and/or flame radiation losses (in the case of a wide sample) [13]. Steady spread with a constant flame length also requires sample burnout that is readily achievable for thin samples.

It appears that concurrent-flow flame spread with a limiting flame length is easier to be obtained in microgravity when the flow velocity is small. Experiments using thin samples with narrow width have shown that this is possible [14, 15]. Although there is no data available for wide samples, two-dimensional model computation suggests a steady spread with a limiting length is possible for thin solids [16]. The model, however, does not have soot radiation which is attributed to flame acceleration in[7].

If a flame reaches a limiting length, the heat release rate due to combustion reaches a maximum. So this can be an important consideration in fire safety. In addition to sample type, its shape and size, the limiting length can be a function of flow velocity, oxygen percentage, pressure, sample heating. One of the objectives of the present project is to understand more on their influence.

2.1 Short duration microgravity experiments and its limitations

Here we review three experiments on thick solids using ground-based microgravity facilities.

Goldmeer et al. [17] studied combustion and extinction of PMMA cylinders during depressurization in low gravity using reduced-gravity aircraft. There samples were PMMA cylinders with a diameter of 1.9cm, length of 2.54cm. Samples were burned in air in a cross flow at a fixed velocity (10cm/s) for different pressures (0.14 atm to 0.98 atm). A type K thermocouple was inserted along the axis of the cylinder to measure the centerline temperature of the cylinder. It was necessary to ignite the samples during the normal-gravity portion of the flight because the time required to establish the flame was longer than the entire low-gravity period. There results showed that as the solid-phase temperature increases, the extinction pressure decreases and the standoff distance at the forward stagnation point increases. There results indicated that the depressurization portion of the International Space Station's fire suppression procedure may temporary intensify the flame by increasing the forced flow velocity. However, any increases in the gas-phase temperatures and reaction rates quickly disappear as the pressure decreases.

Yang et al.[18] studied the low-gravity combustion of supported thermoplastic polymer spheres under varying ambient conditions using reduced-gravity aircraft. The samples were small spheres with diameter varying from 2mm to 6.35mm made of PMMA, polypropylene (PP) and polystyrene. The polymer spheres were supported using a 75 micro meter diameter AL/Cr/Fe alloy wire. The total initial pressure varied from 0.05MPa to 0.15Mpa while the Oxygen concentration varied from 19% to 30% by volume. There results revealed a number of dynamic events including bubbling and sputtering as well as

soot shell formation and breakup during combustion of spheres at reduced gravity. For PMMA, the average value of the ejection frequency was found to be 3Hz and the ejected material was never observed to exist beyond the visible flame of the parent sphere.

Olson et.al [19] studied the transition from normal gravity to forced convective micro gravity environment using the microgravity wind tunnel in NASA's 5.18-second Zero Gravity Research Facility. The samples were PMMA spheres with initial diameter of 2cm and they were ignited at the forward stagnation point in normal gravity. Before releasing the sphere to microgravity, the flame was allowed to spread around the sample. Since the solid phase response time is much longer than the available drop time, the transition to the new environment was limited to the gas phase. Transition from normal gravity to micro gravity caused the flame to quickly change its shape to have a larger standoff distance followed by gradual contraction of the flame length toward the forward stagnation region. There is not enough time to determine whether the flame will eventually go extinction or not.

Limitation of ground-based microgravity testing facilities

Drop towers with several seconds of microgravity time are too short for solid combustion. Solid thermal response times are typically longer. Furthermore, precise determination of the extinction limits requires a gradual approach to limit. There is just not enough time in a droptower to accurately determine the limit. Airplane flying parabolic trajectory provide somewhat longer time (~ 20 s) but with g-jitters. A jitter of $10^{-2} g_e$ produces a random velocity fluctuation of the order of 5 Cm/s. Not only the reduced gravity time is still too short, the gravity level is not sufficient low to determine the limits. Sounding rocket can provide several minutes microgravity test time in its coasting phase

that may be adequate for the testing of many solids. But, the rocket availability is limited. The tests also need to be automated. Data transmission is another concern.

From the above discussion, it becomes apparent that the best platform to carry out solid combustion experiment is the International Space Station.

2.2 Past space experiments of solid fuel combustion

Due to its importance in combustion science and fire safety, several long duration microgravity solid fuel combustion experiments have been conducted before.

2.2.1 Skylab experiment [20]

In the 1970's, Kimzey carried out microgravity experiment in Skylab. In this pioneering work, a variety of materials, mostly in the form of thin sheets was burn. The experiment results were returned in the form of crew comments on voice tapes and video recording of the flame. There results reviled the uniqueness of microgravity solid fuel combustion and excited many research in the following years.

In the 1990's, many scientific experiments took place in space shuttle, Mir space station and sounding rockets [13, 14]. Thin fuels and candles that helped validate the theories developed in the 1980's were burned multiple times as well as some thick solid fuels. The following are several space experiments involving thick solids.

2.2.2 Solid Surface Combustion Experiments (SSCE) [21, 22, 23, 24, 25]

This was conducted in the 1990's in the space shuttle. In this experiment, PMMA samples of four different shapes were burn in quiescent tank which had the volume of $0.39 \times 10^{-3} \text{ m}^3$. The initial pressure and the oxygen mole fraction inside the tank were set on earth and the tank interior was not accessible after the launch.

Short PMMA slabs (25.4mmX3.18mmX6.35mm) were burn at (O_2 mole fraction, Initial pressure) = (0.7, 1atm.), (0.5, 1atm.) and (0.5, 2atm.). These samples had 3 type R thermocouples at the Gas phase, surface and inside of the sample. Long PMMA slabs (59.9mmX3.18mmX6.35mm) were burn at O_2 mole fraction of 0.5 with the initial pressure of 1atm. This sample had 6 type R thermocouples all used in the gas phase. Short PMMA cylinder (2mm x 44mm) and long PMMA cylinder (6.35mm x 40mm) were burn at O_2 mole fraction of 0.5 with the initial pressure of 1atm. These samples did not have any thermocouples attached. The long cylinder is hollow with wall thickness 1 mm from the center. Each sample was ignited using an electrically heated Kanthal wire.

For the short PMMA slab sample, flame spread across the entire sample surface, but with a slowly decreasing spread rate. Flames were eventually quenched deliberately by releasing a spring loaded metal plate to conserve the sample for post-experiment analysis. Numerical modeling of this experiment suggested that the flame will eventually have extinguished due to conduction to the solid and gas phase radiation. Numerical simulation also showed that if the fuel was thinner, the heated layer in the solid can develop sufficiently fast that steady spread can occur. The long PMMA slab sample showed a similar characteristic but in this case, the sample self extinguished after little more than 9 min. Note that the experiments were conducted in a quiescent atmosphere so the relative velocity between the flame and the atmosphere is only the flame spread rate which is very small for the sample thickness used. Theory suggests quenching extinction that indeed was found in these experiments. To have sustained burning in a quiescent atmosphere, molecular diffusion has to be efficient. This is possible only for very small samples such as droplet of particles [\[Ref\]](#).

One surprise from these experiments was the length of time that leads to extinction (minutes). It further shows that long duration microgravity environment is needed to study extinction for thick solid since thicker solids have larger thermal inertia and the heat-up/cooling processes in microgravity are slow.

2.2.3. Diffusive and Radiative Transport in Fires (DARTFire) [26]

This is a low velocity, opposed flow, flame spread experiment done in the 1990's using sounding rocket. The samples for this experiment were black PMMA slab with the dimensions of 20mm x 20mm x 6.35mm.

Type R thermocouples were used for the gas phase and Type K thermocouples were used for the solid phase to measure the flame temperature, surface pyrolysis temperature and in-depth temperature (where?). Cross section of the wind tunnel for this experiment were 10cm x 10cm and the O₂ mole fraction, bulk flow velocity and imposed radiant heat flux were varied.

The results of this experiment showed that the transition (what transition?) to microgravity regime which radiation eventually leads to extinction in at least a quiescent environment for 50% O₂ condition is around 5cm/s. Do you mean a sustained flame with an imposed flow? (Prof. T'ien: The transition is from the classical thermal regime of flame spread over thick PMMA (where the effect of radiation is not big). In the paper "Diffusive and Radiative transport in Fires Experiment: DARTFire", they find out that when the velocity is below 5cm/s, flame spread velocity V_f is no longer proportional to $U^{0.43}$ as the classical theory predicts, but it is proportional to $U^{0.62}$ (U is the incoming flow speed). They say this is because the radiation plays a big role in this low velocity regime and they give a name "microgravity regime".)

2.2.5 Material Flammability Verification Experiment in MIR [27]

This was an experiment conducted by Russian scientists with support from NASA. Three kinds of US-furnished polymers, Derlin, PMMA and high density polyethylene were burned in the Russian-designed combustion tunnel apparatus Skorost in the Mir space station in the late 1990's. All samples were cylindrical with an initial diameter of 4.5mm. The orientation of the sample is to align the cylinder axis with the flow. Flow velocity of the combustion tunnel was manually changeable during the experiment so that the extinction velocity can be searched. The test results concludes that the extinction air-flow velocity for PMMA in the space station environment to be around 0.5cm/s. However, it should be noted that in this experiment, the extruded PMMA samples created a molten ball of liquefied material at the leading edge of the rod. And with time the ball diameter became larger than the rod diameter. This was not observed in the other space experiments. Extruded PMMA will melt and drip extensively in normal gravity burning while cast PMMA only display minimal melt. Nevertheless, the capability of manual flow control was promising since it can smoothly test different flow conditions unlike any of the previous space experiments.

2.2.6 Burning and Suppression of Solid fuels (BASS) [some reference for BASS??]

Burning and Suppression of Solid fuels (BASS) is a microgravity experiment currently being performed in the International Space Station (ISS) (Ferkul any reference?). Using a small wind tunnel inside the Glove Box aboard ISS, air ($21 \pm 1\%$ O_2 and one atmospheric pressure) flow velocity can be varied from 0 to 40 cm/s during the experiment by the astronaut. Because of the small size of the tunnel (10x10 cm cross-section and XX cm long), only small samples are used. These include flat cotton-fiberglass composite fabric, Nomax sheet, PMMA sphere, millimeter thick small PMMA slab and

candle. The only diagnostics are the video and still camera. The tests are on-going. The results obtained so far are quite interesting. In particular, the tests with small PMMA sphere (2cm initial diameter) can serve as the precursor of the present proposed project.

Cast PMMA spheres of initial diameter of 2cm were supported by a rod inserted through the back side. The sample is placed in the flow tunnel with a range of flow velocities. Most of the tests were conducted in a concurrent flow configuration with a heated wire igniter placed around the forward stagnation point. The igniter is retracted after the establishment of the initial flame. As can be seen in Fig. 4, the initial flame is small and blue in color concentrated near the forward stagnation region. As time goes on, the flame tip spreads downstream to the sides of the sample. The flame becomes yellowish with soot. Random sputtering of fuel jets from the surface is then observed. The flame is obviously getting stronger and the local burning rate increases with time. These are consistent with what has been described earlier based on the decrease of internal heating with time.

Insert fig.4 here (I added a figure at the end of this word file. This figure is made of 1cm sphere instead of 2cm case. For the 2cm case, the camera setting was more towards blue and it wasn't capturing the red (test#46-49)). Paul might have better pictures??

Varying flow velocity has a large effect on the appearance of the flame. Flame becomes shorter in slower flow. On a separate maneuver, a small nitrogen jet is issued at the forward stagnation region. The nitrogen extinguishes the flame at the stagnation region; the rest of the downstream flame, however, stays because of the total amount of nitrogen is small due the small jet used. This is true even when the air is turned off. Apparently, the nitrogen jet causes a convective motion that helps to feed oxygen to the

flame. When the nitrogen is turned off, the flame goes out. This sequence further illustrates the importance of flow on flame extinction in microgravity.

Because of the relatively small size of the PMMA sphere sample used (2cm diameter), the distance for flame spreading is limited and accurate spread rate is hard to measure. The sample interior is not instrumented with thermocouples to determine the interior temperature distribution. A more elaborate experiment is needed.

3. The proposed ISS experiment GEL (Growth and Extinction Limit)

An investigation on the flame growth and extinction around a cast PMMA sphere is proposed here. A sphere of large diameter (4cm or 5 cm) has most of the features of a thermally thick solid. Flow around the sphere varies from stagnation point to shoulder to wake, thus encompasses a wide range of aerodynamic patterns. A sphere of this initial size can be re-used several times thus eliminating sample reloading in CIR (a very time consuming task for the astronauts). Upstream flow velocity, oxygen percentage, pressure and sample internal (subsurface) heating will be the parameters varying in this study. The ideal ISS facility that can accommodate this experiment is the Combustion Integrated Rack (CIR) but the proposed large flow tunnel in the Microgravity Glove Box (MGB) can also be used if pressure variation is eliminated as a parameter (In MGB the pressure is fixed at 1atm). The experimental data will be used in the comparison of a theoretical numerical model.

The schematic of the experiment is shown in Fig. 5. The sample sphere supported by a rod is located inside the CIR chamber facing a flow nozzle. The nozzle is connected to flow producing device that generate the velocity of the specific magnitude. Constraint by the

present CIR operation procedure that no active venting is allowed, the flow is re-circulated inside the chamber.

Fig. 5 also shows more details of the sphere sample. Three thermocouples are imbedded inside the PMMA sphere. They are placed at different distances from the surface and at different angular positions. The thermocouple leads go through the hollow supporting tube and are connected to the data recorder. A coiled heated wire igniter will be

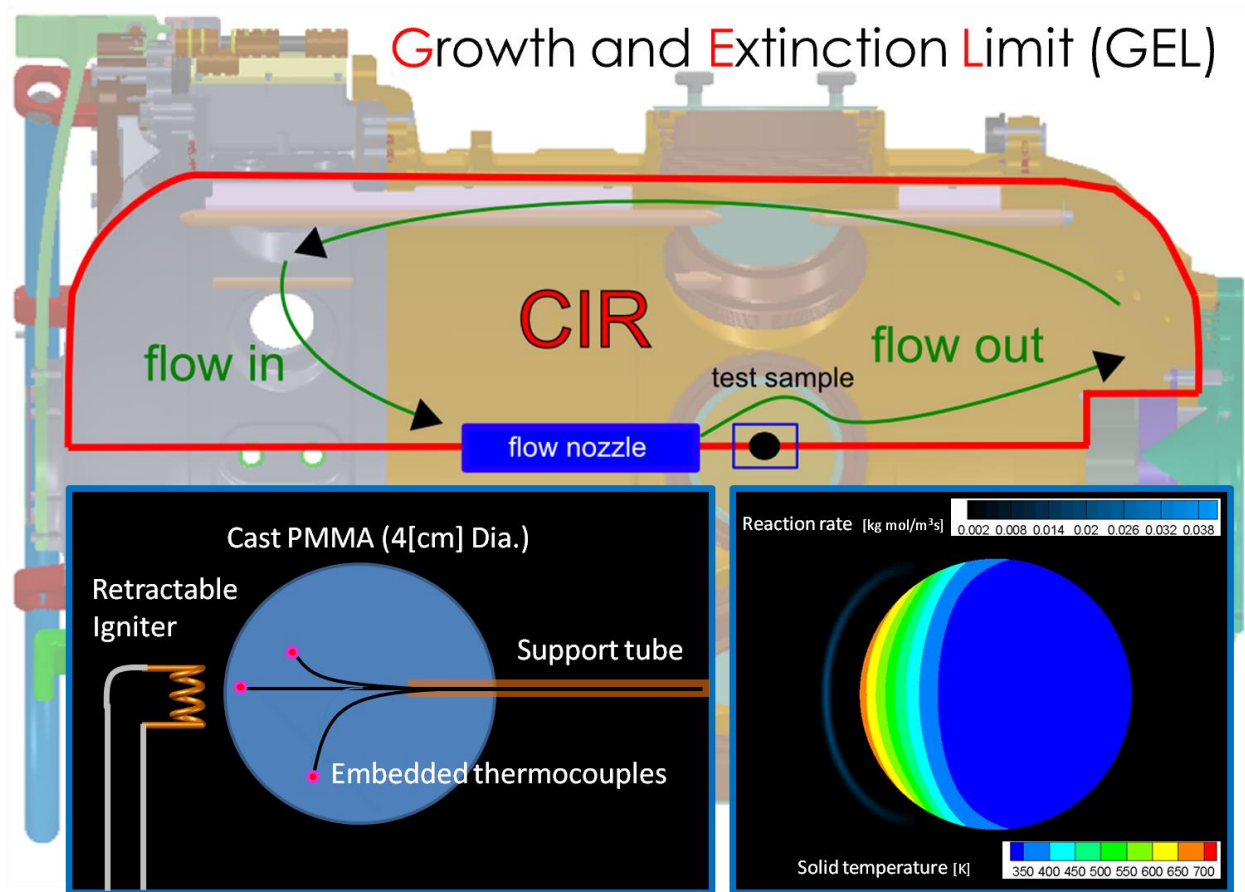


Fig. 5 Schematic of CIR setup for GEL. Upper: CIR chamber (half) with flow nozzle and test sample. Lower left: Sample with imbedded thermocouples and retractable igniter. Lower right: Computed temperature distributions inside the sample and a gas flame represented by the fuel vapor reaction rate contour.

applied at the forward stagnation point region and will be retracted after the initial flame is

established. The flame will then be allowed to grow toward downstream. At a specified condition, the flow velocity can be varied depending on the particular goal of that test. For example, extinction can be achieved by turning down the flow velocity at the nozzle exit.

The diagnostics include a video camera to record the flame shape and growth rate, a backlit camera to record the shape change of the sample, a radiometer to measure the global radiation loss and the thermocouple recordings for the sample interior temperatures.

3.1 Model simulation

A corresponding numerical model will supplement some of the quantities not measured and to assist in the data interpretation. The model has full transient Navier-Stokes equations with one-step finite-rate gas phase combustion reaction coupled with unsteady heat conduction in the sample interior. The solid decomposition obeys one-step zeroth order pyrolysis law. Axis-symmetry is assumed. Surface radiation loss is included but gas phase radiation transfer is as yet to be added. The sample stated as a sphere but will gradually change shape due to un-even surface regression. The program can update the shape change since un-structured grids are used. A commercial program FLUENT has been adopted with added elements for our particular application. A sample calculation is given below.

The top of Fig. 6 shows a simulated flame located on the front part of the spherical sample (4-cm diameter) at a given instance. The vapor reaction rate contours are plotted in blue color to simulate the visible flame. The instantaneous angular position of the flame tip is given by the angle θ . The flame standoff distance from the surface is δ which is a function

of θ . Similar to the flame tip, solid pyrolysis front can be computed as a function of time based on the local burning rate or equivalently the surface temperature.

The bottom of Fig. 6 shows the time history of a simulation with the pyrolysis front as the function of time. The sample is ignited with a heat source at the forward stagnation region for the first 60 s in a 20 cm/s upstream flow. At 60 second, the igniter is turned off. The advance of the pyrolysis front slows down initially but its rate is resumed later. At 90 s, the flow velocity is suddenly reduced in several different scenarios. When the flow is reduced to 10 cm/s, the flame retreats initially but resumes growth later with a slower rate. If instead, the flow is reduced to 2 cm/s, the flame shrinks and becomes extinct. At the intermediate 7cm/s, the flame front is stationary thus yielding a dividing limit between flame growth and extinction. This is of course a function of internal heating, ambient oxygen percentage and pressure.

The bottom right plot in Fig. 5 shows the temperature distribution inside the sample at $t = 198.4\text{s}$ (when I made this figure, I did not have regression into account). Fig. 7 shows the computed temperature time history for the three thermocouples that are placed at (7,0), (5,15) and (3,30) where the first number in the parthesis is the distance from the surface [mm] and the second number is angular position, θ [deg.]. (Makoto: I need this figure) (I added at the end of this file.)

Fig. 8 shows the streamline pattern in the entire CIR chamber at 100 s after the flow is turned on from the recirculation tube. This simulation demonstrated the capability that with Computational Fluid Mechanics (CFD), the flow pattern in the entire test chamber can be included in this combustion experiment. It can be also be used to assess the rate of oxygen depletion and the rate of chamber pressure increase. This information is important

to estimate the time limitation of a test run.

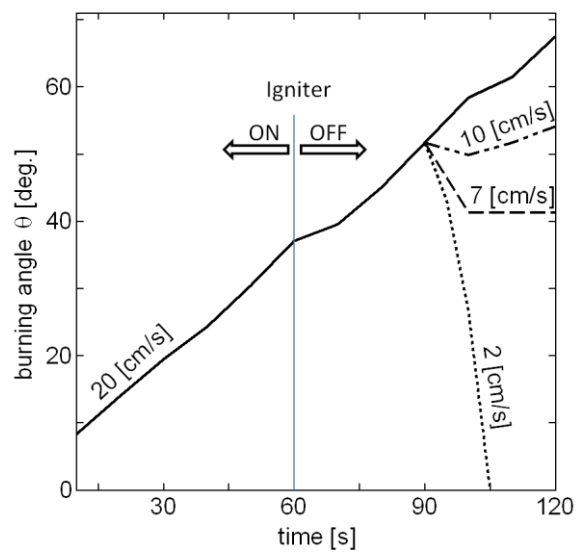
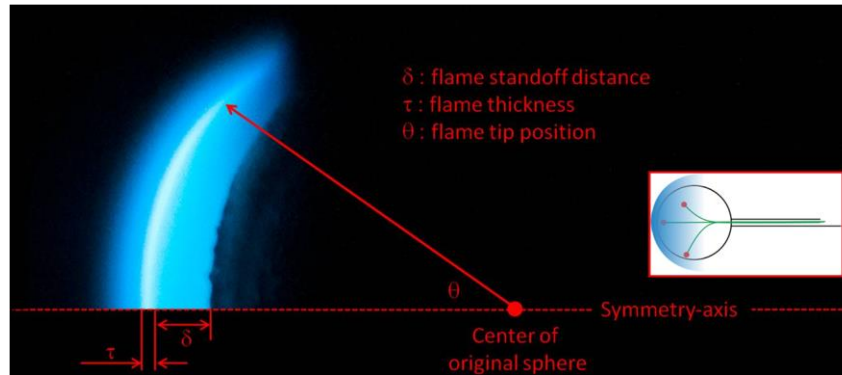


Fig.6 Computed pyrolysis front position vs. time

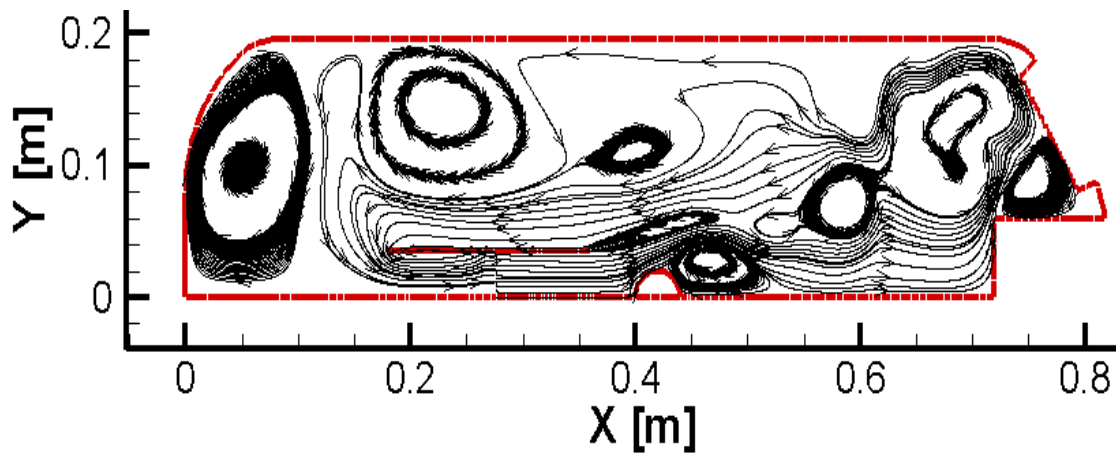


Fig.8 Computed streamline pattern in CIR chamber for 20 cm/s flow at 100s after flow turned-on

3.2 Research objectives

- (1) Experimentally determine the flame growth characteristics (growth rate, flame shape and dimensions) over thick solid fuel as a function of flow velocity, oxygen percentage, pressure and the degree of internal heating
- (2) Experimentally determine the flame extinction characteristics (quenching and blowoff limits) over thick solid fuel as a function of flow velocity, oxygen percentage, pressure and the degree of internal heating
- (3) Establish a high-fidelity numerical model that can be compared with the microgravity results and to serve as a tool connecting normal gravity and microgravity performance.

The sample proposed is cast PMMA sphere of 4 to 5cm diameter that will be instrumented with in-depth thermocouples. These thermocouples are to track the interior

temperature distribution and give a measure of the degree of sample internal heating. A preliminary design of the sample sphere with a tube support and imbedded thermocouples is shown schematically in the inset in Fig. 6.

We plan to sequentially vary the oxygen percentage, the atmospheric pressure and the degree of sample preheating in a series of tests. In each test, the flow velocity will be controlled to see its effect on the flame growth and extinction. It is expected that each test may last several minutes before the flame is extinguished (turning down flow or turn on nitrogen jet). The environmental chamber will be resupplied with a fresh atmosphere before the next test. It is anticipated that the fuel sample can be re-used without opening the chamber door, an advantage of the design. In addition to thermocouples, diagnostics of the flame will be from video, camera, radiometer and possibly IR imaging.

3.3 Science data end product of the flight investigation

The objective of this project can be divided into three groups. In this section, we will address each objective and explain the corresponding science data end products that ensure the accomplishment.

3.3.1 Flame growth (objective 1)

The first objective is to understand the fundamental process of flame growth over thick solid materials in microgravity under different flow velocity, oxygen percentage, pressure and sample heating.

3.3.1.1 Graphs of flame standoff distance as a function of time

3.3.1.2 Graphs of flame thickness as a function of time

3.3.1.3 Graphs of flame tip positions as a function of time

3.3.1.4 Graphs of flame growth rates as a function of experiment parameters

3.3.1.5 Graphs of in-depth sample temperature as a function of time

3.3.2 Flame extinction (objective 2)

The second objective is to understand the fundamental process of flame decay and extinction over thick solid materials in microgravity on flow velocity, oxygen percentage, pressure and sample heating.

3.3.2.1 Graph of the limiting flow speed as a function of oxygen percentage

3.3.2.2 Graph of the limiting flow speed as a function of pressure

3.3.2.3 Graph of the limiting flow speed as a function of preheating level

3.3.2.4 Graph of extinction flow speed as a function of oxygen percentage

3.3.2.5 Graph of extinction flow speed as a function of pressure

3.3.2.6 Graph of extinction flow speed as a function of preheating level

3.3.3 Numerical model development (objective 3)

The last (third) objective is to establish a robust numerical model that can (a) simulate the transient flame development in reduced-gravity experiment; (b) relate material flammability performance between normal and reduced gravity; and (c) examine the relevance of NASA-STD-6001B Test1.

3.3.3.1 Comparison between numerical prediction and microgravity experiment

3.3.3.2 Examine and establish relationships between normal and microgravity results

3.4 Experiment setup and procedure

3.4.1 Experiment setup

The experimental set up will depend on whether to use CIR chamber or the planned new flow tunnel in the Glovebox. The setup for CIR chamber is described here. The use of

flow tunnel in glovebox will be similar to that in the BASS setup.

As indicated in Fig. 5, inside the CIR chamber, a nozzle that can generate a flow with controllable flow rate is needed. A flow speed sensor is required (either mass flow meter or a point measuring device such as a hot wire anemometer). The test sample represented by the lower left figure needs to be supported with wire hook-up to transmit the thermocouple signals. An oxygen sensor and a pressure sensor are needed to ensure that the set environmental conditions are within the acceptable bound and to terminate a particular run as needed. A video camera and a backlight camera will be set up at two of the windows of the CIR chamber. In addition a radiometer will be placed inside the chamber.

3.4.2 Test matrix

3.4.2.1 Test matrix for Objective 1 (flame growth rate) is as follows:

O2%	p (atm)	preheating level	flow velocity
16	1.0	0	5 cm/s
16	1.0	0	10 cm/s
16	1.0	0	20 cm/s
16	1.0	0	30 cm/s
16	1.0	0	50 cm/s
16	1.0	0	80 cm/s
18	1.0	0	10 cm/s
19.5	1.0	0	10 cm/s
21	1.0	0	10 cm/s
16	1.5	0	10 cm/s
16	0.8	0	10 cm/s
16	0.6	0	10 cm/s
16	0.6	1	10 cm/s
16	0.6	2	10 cm/s
16	0.6	3	10 cm/s

3.4.2.2 Test matrix for Objective 2 (extinction limit) is as follows:

O2%	p (atm)	preheating level	flow velocity
16	1.0	0	20cm/s down to ext
18	1.0	0	down to extinction
20	1.0	0	down to extinction
16	0.8	0	down to extinction
16	0.6	0	down to extinction
16	0.6	0	up to blowoff
18	0.6	0	up to blowoff
16	1.0	1	down to extinction
16	1.0	2	down to extinction
16	1.0	3	down to extinction
16	0.8	1	down to extinction
16	0.8	2	down to extinction
16	0.8	3	down to extinction
16	0.6	1	down to extinction
16	0.6	2	down to extinction
16	0.6	3	down to extinction
16	0.6	1	up to blowoff
16	0.6	2	up toward blowoff
16	0.6	3	up toward blowoff

Note: With some cases repeated, it is estimated 50 test runs to complete the project.

Because each sample can be used several times (exact number depends on the specific conditions), the estimated number of fresh samples is 10.

3.4.3 Experiment procedure

A typical run will consist of

- 1) Loading sample and hook-up of thermocouple leads with data acquisition system

- 2) Test and adjust igniter position
- 3) Set up video and backlight cameras
- 4) Set up radiometer
- 5) Turn on flow to desired level
- 6) Make sure pressure and oxygen sensors are working and recording properly.
- 7) Turn igniter on, from the video watch for the appearance of flame. When the flame is big enough (How big? Or wait how long?), Turn off the igniter. If the flame stays, retract the igniter.
- 8) For the preheated cases, using one of the thermocouples (which one) to determine the start of the ignition.

For objective 1 runs (Flame growth)

- 9) Let flame grows until it engulfs the sample or when the growth stops. Turn off the flow to extinguish the flame
- 10) But if oxygen depletes below the specified threshold (How much?) or the pressure rises above a specified threshold (how much?), turn off the flow to extinguish the flame
- 11) After the flame is extinguished, turn on the flow (or nitrogen?) to purge the chamber and to cool the sample
- 12) Refill the chamber with desired atmosphere (oxygen and pressure)
- 13) Start a new test run
- 14) Sample can be used repeatedly until its size is reduced to certain limit (how much?) or it shape is distorted too much (how much?)
- 15) Sample no longer to be used is replaced by opening the CIR chamber

For objective 2 runs (Flame extinction)

- 9b) For the quenching cases, with the set initial flow speed (20 cm/s), let the flame

grows to shoulder region of the sample ($\sim 90^\circ$). Turn down the flow speed to 10cm/s. Wait for 10s, then turn down flow velocity 2cm/s every 10 s until extinction. When the flame becomes very small, the rate of flow velocity decrease may need to be more gradual to obtain a better resolution of the extinction flow velocity.

10b) For the blowoff cases, with the set initial flow speed (20 cm/s), let the flame grow to shoulder region of the sample ($\sim 90^\circ$). Turn up the flow speed to 40 cm/s for 10s, then increase 10cm/s every 10s until blowoff. Prefer to use smaller sample for the blowoff tests. So these can be samples already burned several times.

11b) If blowoff does not occur at the maximum operating flow velocity, turn off the flow to extinguish the flame. After 60s, purge the chamber with nitrogen (preferred) or air and cool the sample before the next test.

12b) Replace sample when needed.

3.5 Experiment Requirements

In this section, specific requirements of each component of the flight experiment are discussed.

3.5.1 PMMA sample

4-cm cast PMMA spheres as the solid material samples with hollow steel supporting tube inserted at the center. It needs to be aligned with respect to the upstream flow direction. The tube needs to be held in the CIR chamber. The holding device should create minimum flow disturbance in the neighborhood of the sphere.

3.5.2 Imbedded Thermocouples

Three k-type thermocouples are imbedded in the PMMA sample discussed above. The approximate position of these thermocouples will be given by numerical modeling and the exact position will be measured using X-ray. Thermocouple leads will be through the hollow tube holding the PMMA sample to minimize flow and thermal disturbance. Thermocouple connections are required. Thermocouple reading must be monitored since this is going to indicate the level of pre-heating. For selected cases, we would like to keep the thermocouples on for hours after the combustion in order to keep track of the cooling process of the sample.

3.5.3 Hot wire igniter

Retractable coil shaped Kanthal wire igniter applied at the forward stagnation point of the sample sphere. It should be designed to be easily replaceable in case of burn out. Since CIR chamber requires considerable amount of time for component replacement, it is desirable to have multiple igniters installed for backup. Because this igniter will also serve as a preheating device of the sample, it should have the capability to run at low temperature (100°C).

3.5.4 Video camera

Color flame imaging: edge view, FOV: 10x10 cm, minimum framing rate: 10 Hz,

minimum pixel array size: 1024x1024, Light sensitivity: must be able to image the dimmest anticipated flame, mused on low-pressure, 1-g and/or microgravity tests. This edge view image is used for flame tracking.

3.5.5 Still camera

TBD.

We will manually specify the stings to maintain consistency between different pictures.

3.5.6 Back light (One for video camera and one for still camera.)

LED backlighting to determine changes of dimension and shape of the PMMA sample during and after the test. Frequency of the light ON/OFF is TBD.

3.5.7 Radiometer

TBD

3.5.8 Flow speed monitoring and control

Mass averaged speed of the upstream flow must be monitored and controlled. Record flow speed during test to ± 0.1 cm/s at 1 Hz. Precision: 0.25 cm/s for 2 and 5 cm/s; 0.5 cm/s for 10 cm/s; 1.5 cm/s for 30 cm/s; 3 cm/s for 50-100 cm/s. It is desired that the flow speed to be verified in real-time, e.g. by using a low-speed anemometer, since the flame may affect the flow speed. Flame shrinking and extinction are obtained by stepwise reduction of flow velocity in otherwise growing flames. This requires the interaction of the ISS crew.

3.5.9 Initial oxygen mole fraction control

16%, 18%, 20% and 21% condition will be used with $\pm 0.25\%$ precision.

3.5.10 Initial pressure control

0.6, 0.8 and 1.0 atm condition will be used with ± 0.02 atm precision.

3.5.11 Pressure and oxygen monitoring

Pressure rise during experiment should not be greater than 10 % of specified value.

Oxygen depletion should not be more than 10 % of specified value.

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Appendix.1 List of Long duration microgravity solid fuel experiments

Skylab Experiments [1970's]

SL4 (SLM-3)-M479

Aluminized mylar sheets (5), Nylon sheet (5), Neoprene coated nylon fabric (5), Polyurethane foam (5), Bleached cellulose paper (5), Teflon fabric (5), Two Papers with a gap in between (7)

Space Shuttle Experiments [1990's]

Solid Surface Combustion Experiments (SSCE)

PMMA slabs (7), PMMA cylinder (2), filter paper (5)

Mir Space Station Experiments [1990's]

Forced Flow Flame Spread Test

Thin cellulosic sheets of fuel (4), Electrically heated conventional wire(4)

Opposed Flow Flame Spread (OFFS)

Cylinders of paper (8)

Candle Flames in Microgravity (CFM)

Candles in different configurations (over 75)

Skorost (Joint project with Russia)

Delrin (4), PMMA_extruded? (4), High density polyethylene (4) , All cylinders and slabs.

Sounding Rocket Experiments [1990's]

Diffusive and Radiative Transport in Fires (DARTFire)

PMMA slabs (8)

International Space Station experiments [2010's]

Burning and Suppression of Solids (BASS)

SIBAL (17), PMMA Sphere (12), PMMA slab (4), Candle (8)

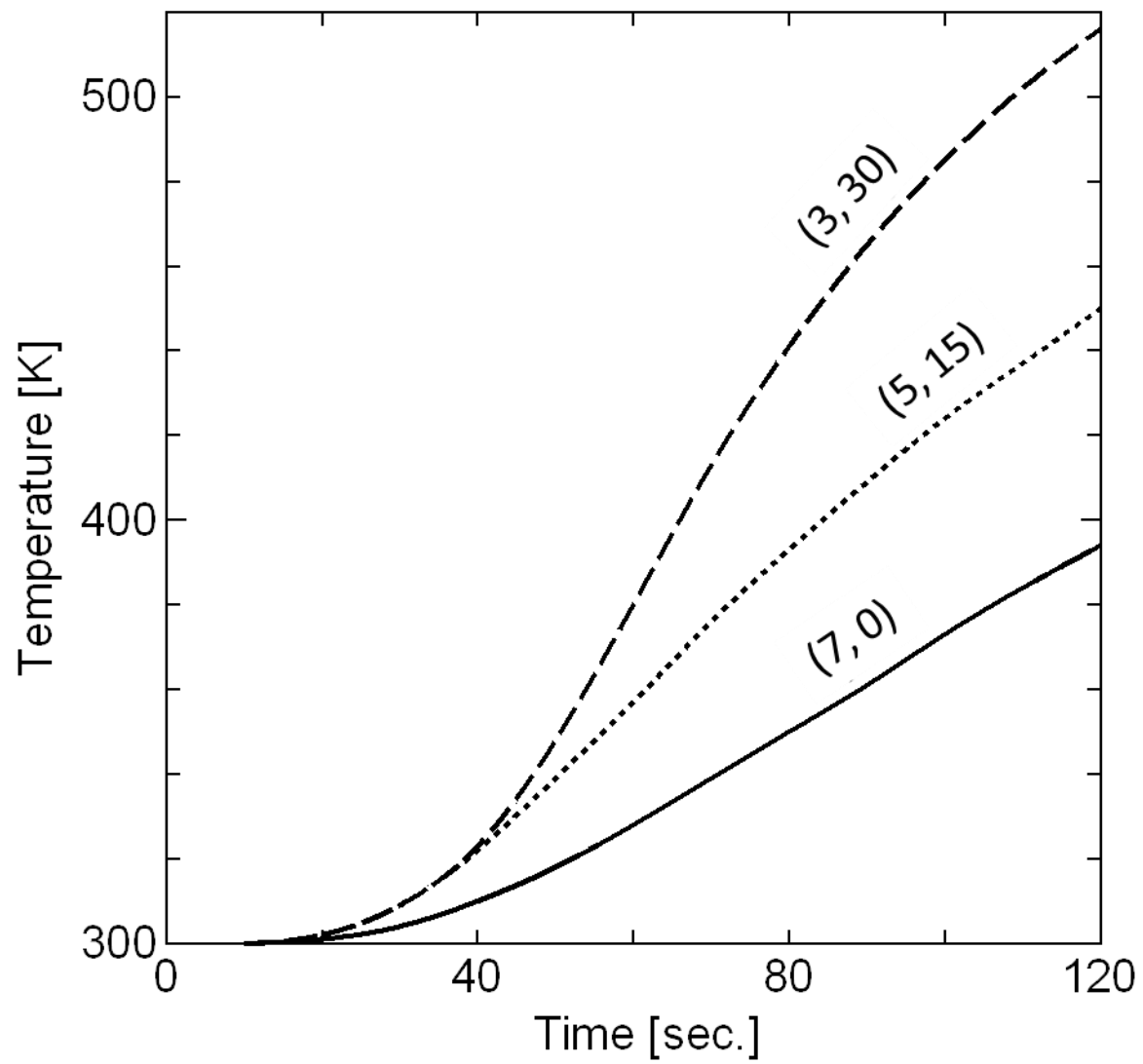


Fig.7 Predicted temperature reading from Thermocouples.

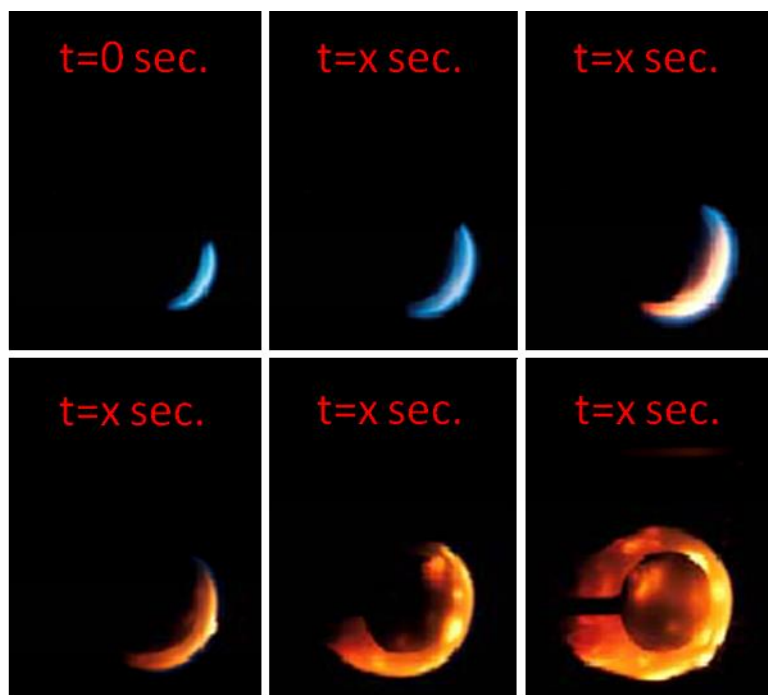


Fig.4 This figure is created from test point 45 data (which is 1cm sphere)